

MATHEMATICAL MODELLING TO PREDICT THE RESIDUAL STRESSES INDUCED IN MILLING PROCESS

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ABSTRACT

Residual stresses prediction has been challenge over the years. Many models have been developed in order to predict the residual stresses. Research has been taking place in this field since many decades. Numerical, experimental as well as analytical models have been developed to determine the nature and magnitude of the residual stresses. In the present work, the authors have made an attempt to build a mathematical model using statistical techniques. The difference between the predicted and the experimental values are in good agreement and the error percentage is less than 15%. The statistical parameters required to ascertain that the developed model are in good agreement to the standard values. The novelty of the work is that, proper procedure has been followed to ensure that the residual stresses induced by the primary manufacturing processes to prepare the specimen is made minimal so that the results are not biased. The future work of the work is to optimize the machining parameters using optimization techniques for which the mathematical model developed in this work will serve as the objective function.

KEYWORDS: Residual Stresses Prediction, Statistical Parameters Required & Objective Function

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INTRODUCTION

Machining is one of the important processes to produce net shape components. During the machining process, the component undergoes many changes. It undergoes physical as well as metallurgical changes. One of the crucial parameters of importance is the residual stresses induced during machining. Studies on residual stresses are existing since 1960s, even though the study on residual stresses is four decades old, all over the world lot of research is happening in the area of residual stresses and prediction of such stresses in both nature and magnitude. The authors of the present work are evolving methods to develop models to predict the residual stresses that are induced in various machining operations. The authors are working on Finite element methods to develop models to predict such stresses as it is less expensive and apart from residual stresses other important aspects of machining can be predicted using the Finite element model. However, the present work is developing a mathematical model using statistical methods to predict the stresses.

LITERATURE

Machining has been part of manufacturing since time immemorial. Understanding the aspects of

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machining is very important for the optimization of the outcome of the process. Machined components are put into function at different working environments. The life of such of the components is determined by various factors like, working conditions, physical nature, metallurgical nature etc. Stresses that remain within the component after the removal of the working forces are termed as residual stresses and it has a significant role in the life of the component [1]. There are many factors, which affect the induced residual stresses. Researches in the past show that the cutting parameters, tool geometry, wear, coating on tool all effect on the residual stresses [2]. While some authors are trying to study the effect of different parameters on the residual stresses, some are trying to find out the effect of sequential cuts on the residual stresses and only few works have been carried out in this area leaving a large scope for future exploration [3–5].

Research on residual stress are being carried out in two front, one is experimental level [6–8] and the other is on simulation level [9]. The experimental level being expensive, the simulation level is rather time consuming. Another aspect of research on residual stresses is the modelling of predictive models, analytical as well as numerical [10,11]

Although there are numerous models available there is not much consensus among the researchers about the accuracy of the model [12]. Understanding the need to have a model which is more practical and reliable the authors have made an attempt to develop model to predict residual stresses using Finite element analysis [13]. However, it was found that the Finite element model has some limitations. Majority of the works are using the orthogonal cutting model to predict the residual stresses [14–16], but there is certain level of drawback in such models, when it comes to machining, it is invariably oblique cutting which is happening, but it is assumed that orthogonal cutting takes place for simplification purposes. As mentioned earlier the authors of the present work have developed a 3d model, which closely captures the oblique cutting. In the present work, the authors have made an attempt to develop a mathematical model is order to overcome the difficulties faced in determining the residual stresses that are induced during machining. The novelty of the current work is that, it is simple and at the same time care has been taken to ensure that residual stresses were not present before machining, which if present may bias the results obtained.

DESIGN OF EXPERIMENTS

Design of experiments, familiarly known as DOE is a tool used by many researchers across the globe to design a set of experiments, which captures the effect of many experiments. It reduces the need to do numerous expensive experiments and saves a lot of time. In the present work, the residual stresses induced due to the milling process is considered as the dependent variable and the cutting parameters as the independent variables. For the purpose of design of experiments, three factors and three levels were considered. Taguchi technique was used to formulate 9 different experiments (L9 orthogonal array is considered). The different factors and the level considered is shown in Table 1.

The designed set of experiments and the corresponding responses is given in Table 2 in coded form.

Table 1: Independent Variables and their Respective Levels

Factors	Level I	Level II	Level III
Speed, rpm	355	500	710
Feed, mm/min	20	40	80
Depth of cut, mm	0.2	0.3	0.5

Table 2: Design of Experiments and Corresponding Responses

Experiment No	Factors and Levels			Residual stresses (MPa)
	Factor 1	Factor 2	Factor 3	
1	1	1	1	-299.4
2	1	2	2	-205.5
3	1	3	3	-391.3
4	2	1	2	-350.0
5	2	2	3	-170.0
6	2	3	1	-378.6
7	3	1	3	-222.3
8	3	2	1	-585.3
9	3	3	2	-374.9

RESIDUAL STRESSES MEASUREMENT

The experiments were conducted in the order as shown in Table 2. There are various destructive as well as non-destructive method to quantify the residual stresses in the machined component. Irrespective of method of measurement, care must be taken to ensure that the components under study were free from residual stresses prior to machining. To ensure that the components were free from residual stresses, prior to machining the components were subjected to heat treatment (annealing) to relieve the stresses that could have gotten arrested within the component as a consequence of the primary manufacturing methods.

X-ray diffraction method was used to measure the residual stresses. It is one of the non-destructive methods to determine the residual stresses. It is more accurate when compared with destructive methods of testing. The specimen size that is required for measurement is a square work piece of 24 mm side and 4 mm thick. The machined specimen is shown in Figure 1.

**Figure 1: Machined Specimen**

The specimen was cut from a 50 mm by 60 mm plate of 6 mm thick. The final dimensions were obtained using milling operations. Further as mentioned above the specimen was subjected to annealing. It was heat treated at 750 degree Celsius for 4 hours and allowed to cool in the furnace itself. After annealing the residual stresses was measured and it was found to be 5.6 ± 4.5 MPa (compressive in nature).

After ensuring that the residual stresses are very minimal, the specimens were numbered from 1 to 9. The experiments were performed as per the run order obtained using the Taguchi technique using commercially available software Minitab. Residual stresses were measured, which is tabulated in Table 2. The negative sign indicates that the stresses are compressive in nature.

MATHEMATICAL MODELLING

The Purpose of mathematical modelling is to predict the residual stresses. The measurement of residual stresses that are induced in the components in machining as explained in the previous section is an expensive method and meticulous effort is needed to ensure that the results obtained are precise and accurate. A lot depends on the specimen preparation and measurement, hence a mathematical model will help us to predict the residual stresses for a particular machining condition. This will save a lot of time and energy. Using the regression analysis tool that is available in the commercially available software Microsoft Excel, the regression analysis was performed. The regression analysis details are shown in Table 3 and Table 4.

Table 3: Summary Output of Regression Analysis

Regression Statistics	
Multiple R	0.929447
R Square	0.863871
Adjusted R Square	0.782194
Standard Error	58.88143
Observations	9

Table 4: ANNOVA

	df	SS	MS	F	Significance F
Regression	3	110008.6	36669.54	10.57666	0.013232294
Residual	5	17335.12	3467.023		
Total	8	127343.7			
	Coefficients	Standard Error	t Stat	P-value	
Intercept	-380.647	97.06206	-3.92169	0.011163	
Speed	-0.28181	0.134676	-2.09249	0.090613	
Feed	4.114405	0.786836	5.229048	0.003384	
Depth of Cut	14.52381	157.3673	0.092292	0.930049	

From the analysis the mathematical model can be derived as shown in Eq. (1)

$$\text{Residual stresses} = -380.75 - 0.28 \text{ speed} + 4.11 \text{ feed} - 14.52 \text{ depth of cut} \quad (1)$$

RESULTS AND CONCLUSIONS

A mathematical model has been developed using statistical technique for predicting the residual stresses induced during milling of AISI 1045 steel. It was observed that the percentage of error for 90% of the experiments was less than 15%. The measured values, the values predicted by the mathematical model developed and the error is shown in Table 5.

Table 5: Comparison between Measured and Predicted Values

Residual Stress (MPa)	Predicted Value(MPa)	Error
-299.4	-270.4	-5%
-205.5	-220.0	28%
-391.3	-391.3	0%
-350.0	-350.2	-1%
-170.0	-161.8	-9%
-378.6	-411.2	-15%
-222.3	-222.3	-12%
-585.3	-565.3	16%
-374.9	-384.9	-9%

The normal probability plot is shown in Figure 2. The plot indicates that the measured values are normally distributed. From the statistical analysis, the R-square value and the Adjusted R-square value are high enough to conclude that the model is close to practicality. ANOVA shows that *Significance F*, value is 0.01 which is below the recommended value of 0.05 indicating that the factors considered is actually affecting the dependent variable, that is machining induced residual stresses.

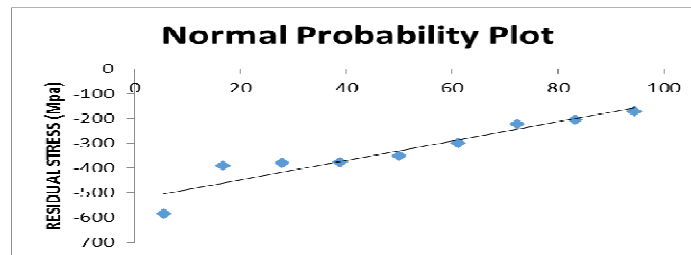


Figure 2: Normal Probability Plot

As seen in Table 2. The *P* value for speed is 0.09 and that of feed is 0.003, which is indicating that these factors significantly affect the dependent variable as compared to the other factor, depth of cut in the range that is considered. The mathematical model that is developed is very close to the actuality. Using the mathematical model to predict the residual stresses is a dependable way than conducting expensive experiments. The authors of the work are also working on Finite element model to predict the stresses. Since a lot of researches are happening in this area, development of a model is very relevant. The work can be further extended to understand the effect of other parameters such as tool designation, cutting condition (dry or wet) etc. on the stresses, also the optimization of critical parameters that affect the residual stresses.

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